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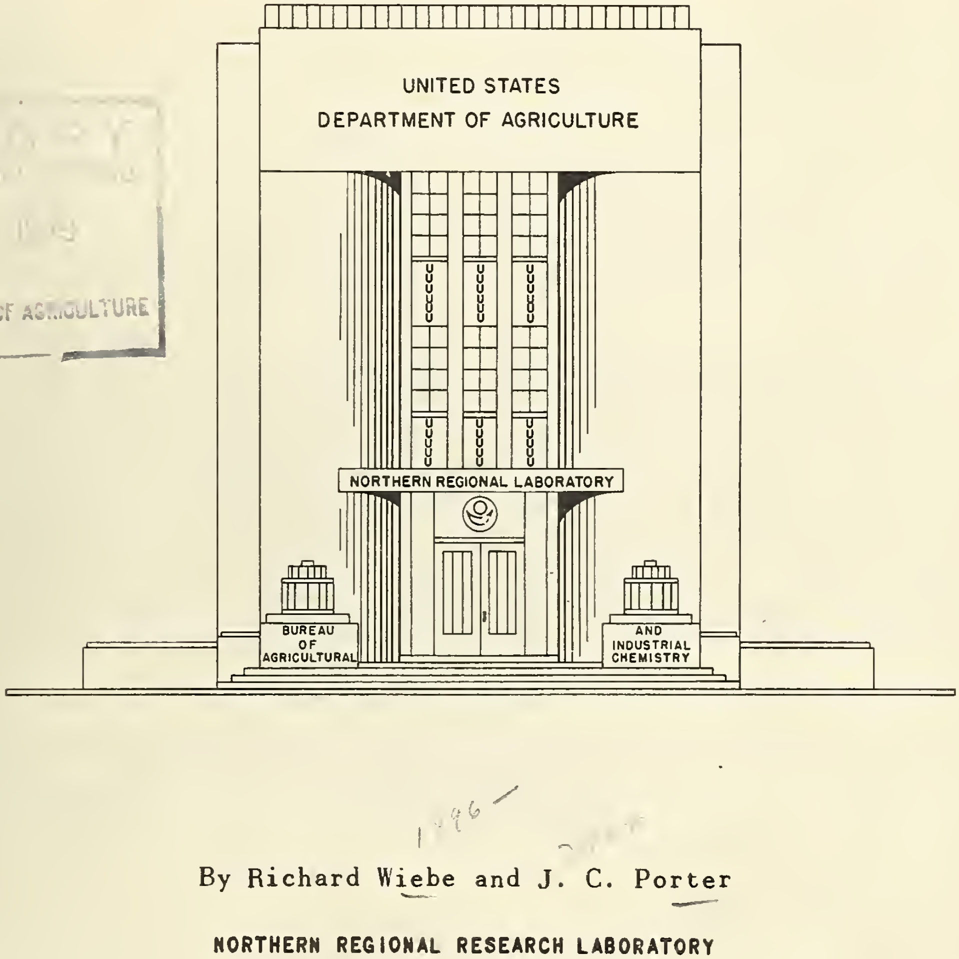
UNITED STATES DEPARTMENT OF AGRICULTURE
Agricultural Research Administration
Bureau of Agricultural and Industrial Chemistry

ALCOHOL-WATER INJECTION FOR SPARK-IGNITION ENGINES



1946

By Richard Wiebe and J. C. Porter

NORTHERN REGIONAL RESEARCH LABORATORY
PEORIA, ILLINOIS

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INTRODUCTION

The purpose of this bulletin is to present, in addition to technical data on alcohol-water injection, a general background of the problems. In a preliminary way it will be shown that the use of alcohol-water injection in conjunction with gasoline may be one of the steps which might serve as a possible market for alcohol from agricultural materials.

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According to the Bureau of Mines Monthly Petroleum Forecast of December 1948, domestic demand for motor fuel rose in the United States from 794.8 million barrels of 42-gallon capacity in 1947 to an estimated 872.6 million barrels (equivalent to 36.649 billion gallons) in 1948. Except for their considerable size, these figures are quite meaningless in themselves. However, a statement that last year 2 billion barrels of crude oil *(11)*[3] were taken from a total estimated reserve of 24.8 billion barrels *(12)* is more significant. If this were taken literally, simple arithmetic would tell us that we will run out of oil in 12-1/2 years if the present rate of production could be maintained (which, of course, would not be physically possible).

Fortunately, this calculation is not correct, but we do not know how wrong it is. One writer *(18)* has drawn a very optimistic picture in stating that "No one gets particularly upset and worries about eating next week because his neighborhood grocer has only a few days' supply of food on the shelf. New oil supplies are being located faster than we are using up the oil on the shelf. By means of new discoveries and further exploration of known oil pools we found during 1947 more than 4 billion barrels of new oil..." Neither of his statements is completely reassuring if analyzed more fully. The first requires simple faith--shaken rather severely during the late war--and the second ignores the fact that for some time most of the expansion of our reserves has come from extensions of known pools rather than from new discoveries.

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[1] Report of a study made under the Research and Marketing Act of 1946.

[2] One of the laboratories of the Bureau of Agricultural and Industrial Chemistry, Agricultural Research Administration, U. S. Department of Agriculture.

[3] Italic numbers in parentheses refer to Literature Cited, page 30.

Such an expansion is likely to show diminishing returns with time. R.J.S. Pigott *(27)* believes that neither the pessimistic view of approximately 12-1/2 years nor the optimistic estimate of 100 years is warranted and prefers the safe middle of 40 to 50 years, admitting frankly that there is no sound basis for such a compromise. The basis for most optimistic or "realistic" estimates is the fact that the ratio of an annual consumption to estimated resources has remained reasonably constant for the past 25 years, and from this it is concluded it must remain so for another "X" years, and "X" is anybody's guess. On the basis of past record, it is indeed difficult to prophesy without being exposed to ridicule.

New oil deposits will be found, imports will increase. Tanker construction is up. Synthetic fuels from coal and oil shale are probable in the near future *(15)*. But in spite of all this, it would seem imperative to investigate whether, in the continuance of the ever-increasing consumption of a valuable and irreplaceable commodity, every effort is being made to conserve our resources. The answer is an emphatic "no."

Even a cursory examination of our conservation practices, or lack of them, reveals an enormous waste to which everyone contributes. There is no difficulty in showing where savings can be effected in production as well as in consumption of liquid fuels. Perhaps the word "waste" is slightly inappropriate here; it is not used in the sense of condemnation but to emphasize a situation which can be abated by means now at our disposal. Of course, we may adopt either the extreme point of view of Wallace Pratt, former consultant for the National Security Resources Board, who has suggested an arbitrary 20-percent cut in production, or again of the man who, in pure desperation, sees no alternative but "to keep on using gas until we just run out." However, the general attitude does seem to be much better expressed by Herman Melville when he says in ***Moby Dick:*** "Ah! how cheerfully we consign ourselves to perdition!"

Any present or future temporary oversupply of many petroleum products and the consequent demand for reducing imports, or even a drop in gasoline and fuel-oil prices, do not affect our arguments. The problem of depletion of our reserves still stands, regardless of future discoveries. To illustrate "sudden" changes of outlook in the availability of valuable resources, the cases of iron and coal may be quoted. Our high-grade iron deposits are disappearing so rapidly that the outlook is definitely discouraging. Second-grade iron deposits fortunately are still large but their recovery means increased investment and greater ultimate cost to the consumer. The large high-grade deposits in Brazil, Labrador, and Sweden, for instance, are questionable sources in an emergency, and in the first two instances will require huge capital outlays. Again, the former optimistic estimate of the availability of coal for 2,000 years has been drastically reduced to a more likely 400 years or less, though direct gasification in the mine for low-grade deposits, a method now being developed by the U. S. Bureau of Mines, promises a possible utilization of marginal deposits not included in the low estimate.

While the depletion of our crude oil reserves is going on, what steps may be taken to conserve them to our utmost ability? In considering various possible steps, it will be convenient to divide them under three headings: manufacture of gasoline, engine and car factors, and driving habits and traffic conditions. All are of almost equal importance, though admittedly the first two are the more tangible, under which greater economy of fuel consumption may be achieved progressively and thus within a reasonable time bring considerable benefits for both producer and consumer. They will be discussed briefly, therefore, mainly for bringing into the picture the possible importance of alcohol-water injection.

MANUFACTURE OF GASOLINE

In the manufacture of gasoline, the octane number of the fuel is our most important criterion of fuel quality. Since octane number has become quite indefinite, some clarification of its meaning is necessary. For several years the "combustion quality" of a gasoline has been designated by two different octane numbers[4], the old "Motor Method" and the new "Research Method." (New only in the sense that it was made recently an A.S.T.M. standard). In practically all commercial gasolines, judging by the Bureau of Mines survey *(7)*, the Research Method octane number is higher than that of the Motor Method. This difference is termed "sensitivity." As stated by McLaughlin and Miller *(26)* the term "fuel sensitivity" is one which is generally used to define the change in the anti-knock value of a gasoline as a function of the severity of the operating conditions used, and the Motor Method is more severe. Lovell *(25)* in his comprehensive review of octane numbers mentions that there are some hydrocarbons which show a reverse behavior, hence there must be factors other than higher mixture temperature and spark advance. Table 2 shows the more highly cracked gasoline to be more sensitive and in the last column the sensitivity of the fuel equals 82-72=10. Many agricultural motor fuels are also highly sensitive. The Research Method and Motor Method ratings of ethanol are equivalent to a gasoline of 100 octane number plus 1.4 milliliters of tetraethyl lead (T.E.L.) per gallon and 91 octane number, respectively *(14, 30)*, indicating a sensitivity greater than 10 (without going into the details of converting octane to performance number scales). This, however, brings up one more important fact, namely, that each octane unit becomes increasingly valuable as the octane number goes up. One octane number in the range between 90 and 100 "accomplishes" much more than one between 60 and 70, but only in an engine built for the utilization of these higher octane fuels.

As a matter of interest, table 1 gives the average octane numbers for regular and premium gasolines in three sections of the country as published by the Bureau of Mines.

Since there appears to be a desire for higher and higher octane fuels, it is pertinent to look into how they are being made. D. P. Barnard *(5)*, in reviewing the "octane problem" recently, stated that "no known refining method achieves octane number improvement without some sacrifice in the amount of gasoline from a given quantity of crude.... Unfortunately, it also happens that the fuel manufacturer is faced with progressively greater manufacturing difficulty with each unit of octane-number increase. Once upon a time, it was relatively a simple matter to add tetraethyl lead to the gasoline then being manufactured and increase its knock rating 5 to

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[4] The octane number of a gasoline is equal to the percentage by volume of isooctane in a mixture of isooctane and *n*-heptane when the gasoline and this mixture show the same knock severity (knock intensity) in a specially designed single-cylinder variable compression engine.

TABLE 1.--*Average values of different brands of gasoline (summer of 1948)*

Region	Tetraethyl lead		Resulting octane number			
			By Research Method		By Motor Method	
	Milliliters per gallon added		A.S.T.M. D-908		A.S.T.M. D-357	
	Regular	*Premium*	*Regular*	*Premium*	*Regular*	*Premium*
Northern Illinois[1]	1.50	1.79	78.5	84.1	74.2	78.4
Central Mississippi[2]	1.69	1.91	78.5	85.5	74.6	79.2
Central Plains[3]	1.59	1.90	76.9	83.1	73.2	77.7

[1] Northern Indiana, northern Illinois, eastern Iowa, and Wisconsin.

[2] Western Kentucky, southern Indiana, southern Illinois, and eastern Missouri.

[3] Nebraska, central and western Iowa, northwestern Missouri, and northern Kansas.

Source: National Motor Gasoline Survey, Summer 1948. U.S. Dept. Int. Bur. of Mines, RI 4444. December 1948.

10 units. At present gasoline quality levels, however, the same amount of lead will not give as great an improvement in knock rating. Further increases in octane rating necessitate going into basic refinery operations. The solutions in individual refineries will vary widely but they have several points in common: All require expensive equipment, large quantities of steel, much time to execute, and additional sacrifice in yield per unit of crude." The following table, from an article by H. M. Holaday *(20)* and coworkers, shows what may be experienced in actual operation.

As shown in this table, the volume of gasoline obtainable from a given volume of stock diminishes as the octane number is increased. The indicated 3 ml. T.E.L./gal.

TABLE 2.--*Yield octane relationships for re-forming 250°-400° F. Oklahoma City type naphtha*

Thermal re-forming at 800 p.s.i. (gauge) and 1000° F.				
Volume percentage re-formed gasoline (based on naphtha charge) (Reid vapor pressure—10 p.s.i. absolute)	100	90	80	70
Motor Method octane number clear	36	60	68	72
+ 3 ml. T.E.L. per gallon	—	75	81	83
1939 Research octane number clear	38	62	75	82
+ 3 ml. T.E.L. per gallon	—	78	88	93

is about double the average lead content of present-day gasoline (see table 1). Replacement of all thermal cracking units (60 percent of existing capacity) by catalytic units would give a higher yield; however, the possible scrapping of such an enormous investment should not be taken lightly. Smaller refineries might not be able to undertake such a radical program, although small-sized catalytic units are being developed.

ENGINE AND CAR FACTORS

The principal engine and car factors which lead to greater fuel economy or more miles per gallon are given in table 3, taken from an article by W. S. James *(22)*.

TABLE 3.--*Estimates of increased miles per gallon by various means*[1]

Item	Range	Approximate average
	Percent	*Percent*
Reduction of heat loss and incomplete combustion	10-40	15
More accurate carburetor metering	5-50	15
Fewer traffic stops	10-25	20

DESIGN MODIFICATIONS

	Ideal maximum		Present possible	
	Road load	Wide open throttle	Road load	Wide open throttle
	Percent	*Percent*	*Percent*	*Percent*
Overdrive	[2]+20	+37-0	+13	+26-0
Lower wind resistance	+9	0	+8	0
Weight reduction of 15 percent:				
Smaller engine	+17	+15	+16	+16
Axle ratio change	+12	+13	+10	+12
12:1 Compression ratio:				
Smaller engine	+33	+22	+30	+17
Axle ratio change	+40	+24	+36	+18
Supercharging:				
Smaller engine	+17	0	+17	0
Axle ratio change	+24	-5	+17	-12
Automatic transmission . . .	+48	0	+37	0
ESTIMATED				
Smaller engine				
10:1 compression ratio	+25	+16	+22	+12
8:1 compression ratio	+12	+8	+11	+6

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[1] See *(22)*.

[2] Increase in efficiency is denoted by "+" sign and +37-0 indicates that improvement may vary all the way from +37 to nothing.

Reduction of heat loss and incomplete combustion may be accomplished by higher compression, better combustion-chamber design, better spark-advance mechanism, and a "good" gasoline. The remedy for the second and third item is obvious. Overdrive, for keeping engine speed down, is available for many cars. Lower wind resistance needs no comment. Weight reduction simply means a smaller car and consequently a smaller engine, and whether this is practical will depend on popular acceptance. The following item, 12:1 compression ratio, or in general, compression ratios higher than present ones (1948 average was 6.73:1) is the most economical and logical method of improving performance and economy. It is this method which will be emphasized throughout this bulletin. Supercharging is practiced in stationary Diesel engines and aviation gasoline engines, but except in a few isolated instances, automotive engines are not supercharged. There are, however, no insuperable obstacles for doing so. The effect of compression ratio and supercharging on octane number in a specially built single-cylinder engine was demonstrated very clearly by Earl Bartholemew *(6)*. Figure 1 reproduces some of his results and they may serve as a general guide. The following two examples will illustrate the meaning of the chart. At a 6:1 compression ratio and 35 inches of mercury absolute manifold pressure (approximately 5 inches supercharge), this particular engine required an 80 octane number (O.N.) fuel while for the same manifold pressure, but at 8:1 compression ratio, 99 O.N. gasoline was required. If we wish to maintain the octane number constant and increase the manifold pressure (supercharge), the compression ratio must be lowered. Finally, fully automatic transmissions which maintain an engine speed for lowest fuel consumption at all loads will be built some day, but are not here yet.

Increase of compression ratio will be emphasized greatly throughout this discussion. A few remarks regarding some of the principles involved may prove helpful. According to general practice, the compression ratio is considered equal to the expansion ratio. The latter ratio is the significant one in theoretical calculations of cycle efficiencies, and because of valve overlap there is a difference between the compression and expansion ratio. However, we are interested in relative performance and in that case no large errors would result.

The following tabulation showing approximate limiting values of attainable efficiencies for compression ratios from 4 to 16 is taken from a previous publication *(40)* in which this problem is discussed more extensively.

CALCULATED THERMAL EFFICIENCIES AT VARIOUS COMPRESSION RATIOS

Compression Ratio	Thermal Efficiency
4	0.29
6	.36
8	.40
10	.43
12	.46
14	.48
16	.49

Sparrow *(35)* in 1926 investigated the effect of compression ratio upon engine performance and found that the ratio of actual to theoretical gain in going from a compression ratio of 5.3 to 8.3:1 was only slightly lower than 1 or, in other words, relative gain equalled nearly that predicted theoretically. This was confirmed by Bartholemew *(6)* when comparing two engines having 6.1:1 and 8.5:1 compression ratios. An interesting point in this connection was that the use of a lower axle ratio (3.9 instead of 4.4) with the 8.5:1 engine increased the average gain from 12 to 21 percent (see also table 3). Additional evidence was presented by Roensch *(32)* by showing the added improvement in economy (miles per gallon) obtainable with the new General Motors research high-compression engine.

As stated previously, driving habits and traffic conditions are outside the province of this paper, but, of course, driving habits demanding higher and higher performance, often termed "pickup" are diametrically opposed to fuel economy. It is also absurb to provide 85 to 100 horsepower to carry one person around *(1)*.

From the foregoing it is clear that the manufacture of higher octane gasolines is undesirable from the economic point of view and any step in such direction certainly cannot be advocated unless proven to be essential for running engines. It is also clear that certain modifications or improvements in engine and accessory equipment will contribute greatly to fuel economy. However, it would seem a waste of engineering effort to provide engines of higher efficiency at the cost of higher refining losses, since the net effect might be zero. Now it turns out, as shown in figure 1, that for high-compression and supercharged engines high octane fuels are necessary unless another method can be found, and such a method may be alcohol-water injection. Alternative methods may also come into the picture and two such possibilities will be mentioned later.

ALCOHOL-WATER INJECTION

The fundamental principle of alcohol-water injection is simple. The combination of the excellent anti-knock qualities of alcohol, together with the high heats of vaporization of alcohols and water in lowering the intake mixture temperature, will raise the effective octane number of the gasoline. The amount of injection necessary will depend on the increase in octane number desired, the quality of the gasoline, and engine conditions.

At this point a brief historical review is in order. Bertram Hopkinson *(21)* in 1913 mentioned that "It is common practice in oil engines to introduce water along with the oil in order to enable the compression to be raised." He himself injected the water directly into the combustion chamber of a slow-speed gas engine, taking care that the spray was directed against the upper cylinder surfaces. His purpose was to substitute internal cooling for an outside water jacket and to utilize the steam along with the regular charge to increase output. Such an internal water injection method is quite impractical and, of course, for that reason it has not been used. More effective cooling will lower the octane requirement of any engine, and lately more effort is being made to improve this factor. Fred R. Jones in his book, "Farm Gas Engines and Tractors", *(23)* also mentions the use of water to prevent knock[5] in tractor engines at heavy loads. In this case the carburetor is equipped

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[5] Knock is mentioned here repeatedly and it is taken for granted that everybody has heard the sound at least once. Aside from the psychological effect, prolonged severe knock, at any rate, results in damage to the engine through overheating and by the stresses induced by explosive combustion. Preignition may result, stopping the engine before damage is done. There are many variations to the theme.

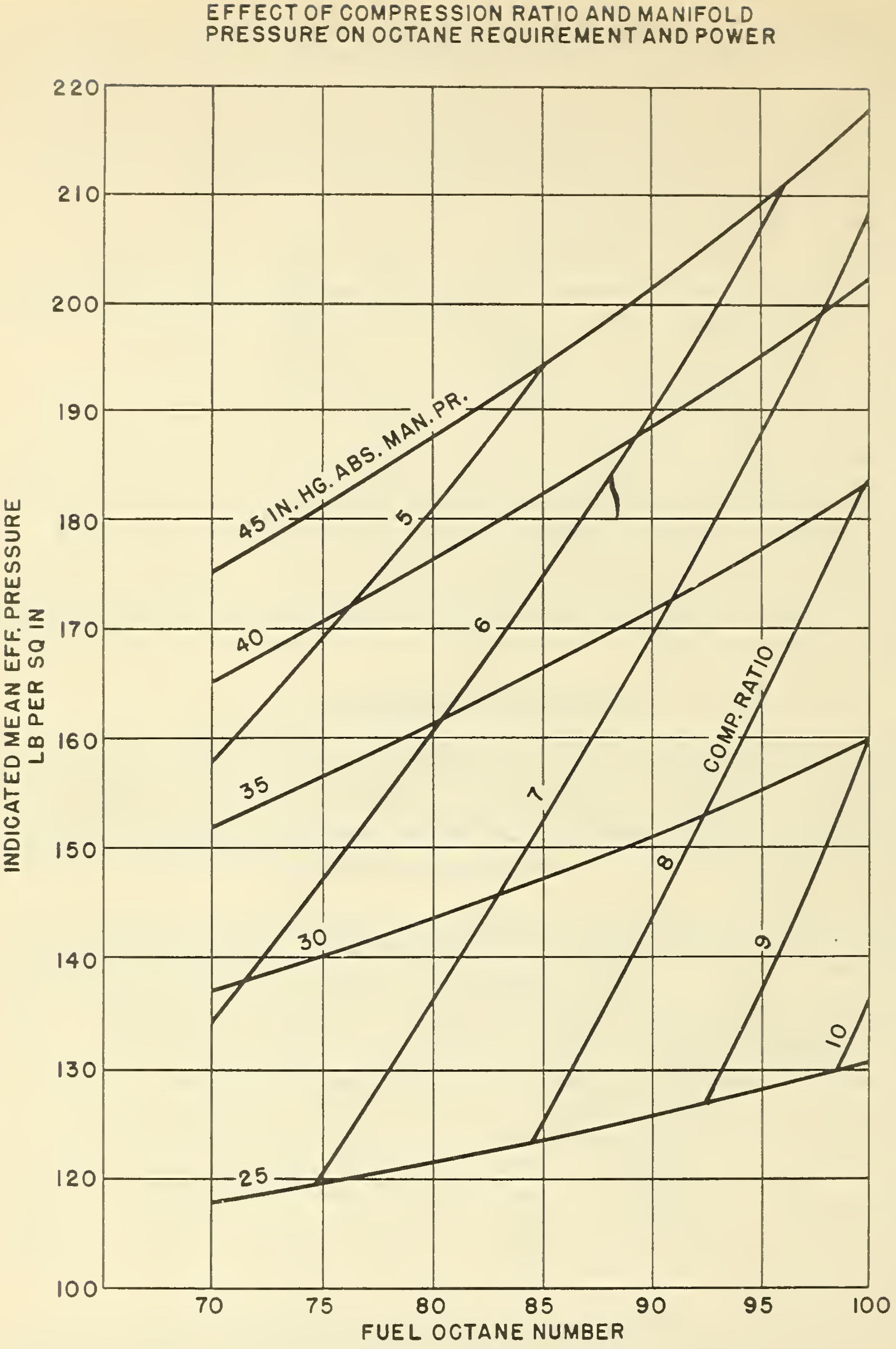

Figure 1.--Relation of knock--limited I.M.E.P. to fuel octane number at maximum power mixture and spark advance. (*See* Bartholomew (*6*).)

with an extra jet and needle valve for manual operation. E. L. Barger *(4)* cautions against the use of an excess of water which always results in reduced fuel economy. Just enough water should be added, he states, to take out most of the knock, or "ping" as it is usually called, to run the engine at "trace" knock, meaning that a slight ping is permissible. Wawrzinick *(38)* found that substituting 95-percent alcohol for water was much superior to using plain water. A smaller quantity was required to overcome knock. There was no power loss at the higher speeds, and fuel consumption was identical with that obtainable with non-knocking gasoline when the heating value of the alcohol was included.

Starting with Kuhring *(24)* and continued extensively during World War II, a large amount of experimental work on alcohol, water, and other "coolant" injection into aircraft engines has been reported, mainly by the National Advisory Committee for Aeronautics. A fairly complete list of references with annotations will be found in a bibliography recently published by this Laboratory *(39)*. (Since these data are of immediate interest to us, no further comments are necessary.)

Since the recent war, interest has been shown in the practical possibilities of alcohol-water injection in automotive engines and the literature has been reviewed in the above-named bibliography to which reference will be made to the published literature only in relevant cases.

Previous work at this Laboratory *(28)* has shown that alcohol-water injection with a "regular" grade gasoline of 72 octane number may be used interchangeably with a 90 octane number fuel if the compression ratio is increased from 7.5:1 to 9:1. A considerable increase in power, as well as lower specific fuel consumption, were noted with the higher compression ratio. This work was confined to one engine in the laboratory. Later results obtained with several engines in the laboratory and on the road, at both part load and full load, are presented and the important factors entering into performance are emphasized. For convenience, a schematic diagram of the injector principle is shown in figure 2. The automatic feature of this and other injectors (see descriptions by A. T. Colwell *(10)* and Van Hartesveldt *(36)*) is based on the fact that between idling and full load the absolute pressure in the manifold changes from a very low value to practically atmospheric pressure or, as it is often termed, from a high to a very low vacuum, the latter being nearly the pressure of the atmosphere. It will be seen in figure 2 that injection is controlled by means of a valve activated mechanically by manifold vacuum and that in this case the alcohol-water mixture is injected above the carburetor. Just as the carburetor evolved from a very simple device, the injector or, better, the alcohol-water carburetor in time will receive added refinement to make it still more adaptable.

When driving on reasonably level road at speeds up to about 40 miles per hour an average automobile engine will operate satisfactorily with a gasoline of 50 octane number, or even lower, hence under such conditions much octane quality, speaking figuratively, is wasted, since we saw in table 1 that the octane number of regular gasoline is around 78/74[6]. However, during acceleration, hill climbing, and in

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[6] This nomenclature will be used to designate the Research Method and the Motor Method octane numbers, respectively. Low-octane commercial gasoline has a low sensitivity and, therefore, octane numbers of both methods are practically identical.

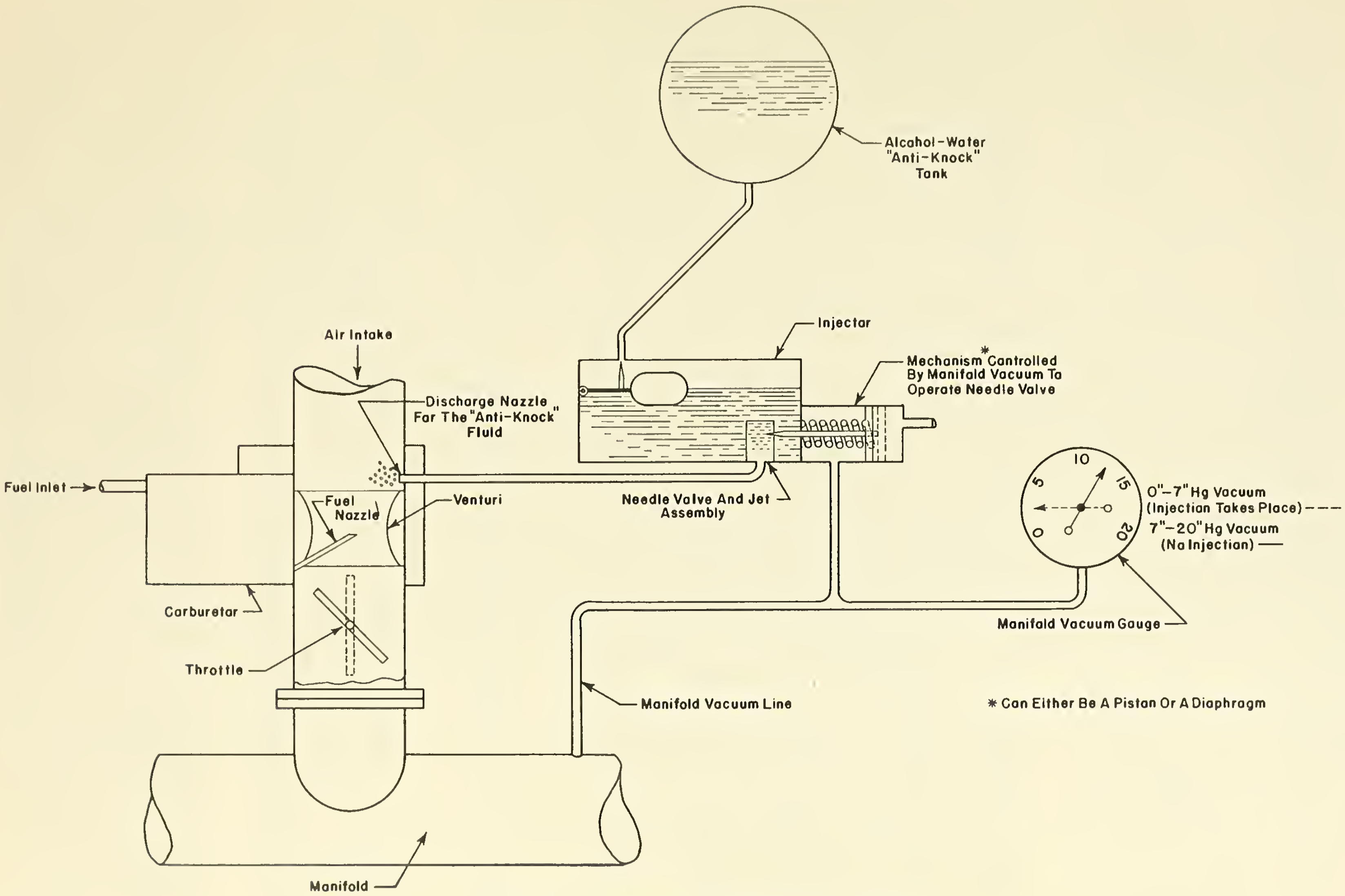

Figure 2.--Diagram of injector principle.

general when the engine is working hard, the full octane value of the fuel may be required. The usefulness of alcohol-water injection consists in supplying this octane difference when needed. The way this may be done was explained when describing the actions of the injector. Whether this is applied to present-day cars using a relatively low-octane gasoline with alcohol-water injection to obtain regular or premium-grade performance, or to the coming high-compression automobile engines where present-day regular or premium gasoline with alcohol-water injection may be necessary, will not be answered here. Sufficient data will be presented, however, to throw considerable light on such possibilities.

Aside from ethanol ("grain" alcohol), methanol ("wood" alcohol), and isopropanol (also a possible grain alcohol, but not manufactured from grain at present) may be

TABLE 4.--*A relative efficiency of various anti-knock mixtures*

Experimental conditions:	1946 Ford V-8 engine High-compression head (8.25:1 C.R.)	r.p.m. = 1800, full-throttle operation Octane requirement = 90 octane reference fuel	Spark advance = 14° Base fuel = 73 reference fuel

Anti-knock mixture composition	Percent by volume	Ratio of anti-knock mixture to fuel by weight for trace-knock operation	Relative efficiency
C.D.[1] ethanol (completely denatured alcohol using C D-12 formula)	100	0.22	100
C.D. (special)	100	.25	88
Ethanol. . . . . Water	85 15	[2].23	96
C.D. ethanol . . . . Water	80 20	.28	79
C.D. ethanol . . . . Methanol	50 50	.19	115
C.D. ethanol . . . . Isopropanol	50 50	.19	115
C.D. ethanol . . . . Methanol . . . . Water	42.5 42.5 15	.24	92
C.D. ethanol . . . . Isopropanol . . . . Water	42.5 42.5 15	.25	88
Ethanol . . . . Isopropanol . . . . Water	42.5 42.5 15	.26	85
Methanol . . . . Water	85 15	[2].23	96
Methanol . . . . Isopropanol . . . . Water	42.5 42.5 15	[2].24	92
Isopropanol . . . . Water	85 15	[2].34	65

[1] C.D. = completely denatured.

[2] Average values for the entire speed range which is quite comparable, however, to the values at 1800 r.p.m.

used for injection, since all of them have high anti-knock qualities. Incidentally all three alcohols are also being made synthetically on a large scale, which would insure a steady supply. Thus, by including water, we have four components, making a large number of combinations possible. The few possibilities presented in table 4 should not be considered necessarily the best nor, of course, the only combinations. In this table, straight, completely denatured alcohol is taken arbitrarily as 100 and the higher the rating in column 3, the better the particular mixture. On this basis, the denatured alcohol with either methanol or isopropanol on a 50:50 basis appears to be the best. However, this is not the final answer, for every combination has not been investigated; distribution of the mixture among the cylinders may be very important, the response of the gasoline (base fuel) as well as the engine itself, all are variables, so that fine distinctions cannot be drawn. Further data are given in figure 3. Under *A* the three solid line curves show the amount of injection as a function of the percentage of water in the alcohol-water mixture for octane increases of 5, 9, and 17 to satisfy the octane requirement of the particular engine which happens to be 90. The octane increase is simply the difference between 90 and the gasoline of 85, 80, and 73 octane number used with injection. Since reference fuels were used, the Motor and Research number is the same for both fuels. The higher the percentage of water or, conversely, the lower the percentage of alcohol (dotted lines), the greater is the amount of injection required and that is also true the higher the octane increase required. For example, a 17-octane increase (90 minus 73) may be obtained with injection with a ratio of ethanol to gasoline of .225 while with straight water the ratio would have to be .50. In this case it is not only necessary to more than double the amount of injection in order to achieve the same octane gain but there is also a distinct loss in power as shown in figure 3-*B*. It often happens that flooding results before an equivalent increase with water alone can be accomplished, as was found in our previous work *(28)*. With reference to this, the work of Rowe and Ladd *(33)* should be quoted: "Full-scale operation has shown that water mixtures in excess of 50 percent by weight of fuel exhibit the tendency of drowning out the engine combustion cycle when operating at rich mixtures. This drowning tendency is best overcome by using water-alcohol mixtures instead of pure water and by operating at best power fuel-air ratios." It should be kept in mind that the engine factor is as important as the fuel. Small octane gains, principally obtained through coolant action, are obtainable with water alone without any significant loss in power, as indicated in figure 3-*B*.

In apparent contradiction, boosts in power have been observed in both water and alcohol-water injection without the apparent need for the concomitant increase in octane value. Kuhring *(24)* reports a gain of 25 hp. because of an increase in volumetric efficiency alone through water injection into a supercharged aircraft engine. Potter, Van Hartesveldt, and also the authors already cited *(29, 36, 28)* found that a slightly higher output was obtainable with alcohol-water injection and regular gasoline, than with the "premium" gasoline needed for trace-knock operation. This has been called "supercharging effect" by Van Hartesveldt and is caused as above by a slight increase in volumetric efficiency through lowering of the intake manifold temperature. Results by Van Hartesveldt *(36)* indicated that tetraethyl lead in alcohol-water mixtures will reduce the amount of mixture necessary to eliminate knock. In this connection table 5 is of interest.

This shows the effect of both alcohol and lead on the octane numbers of four specially prepared gasolines. Indications that these mixtures of diisobutylene and

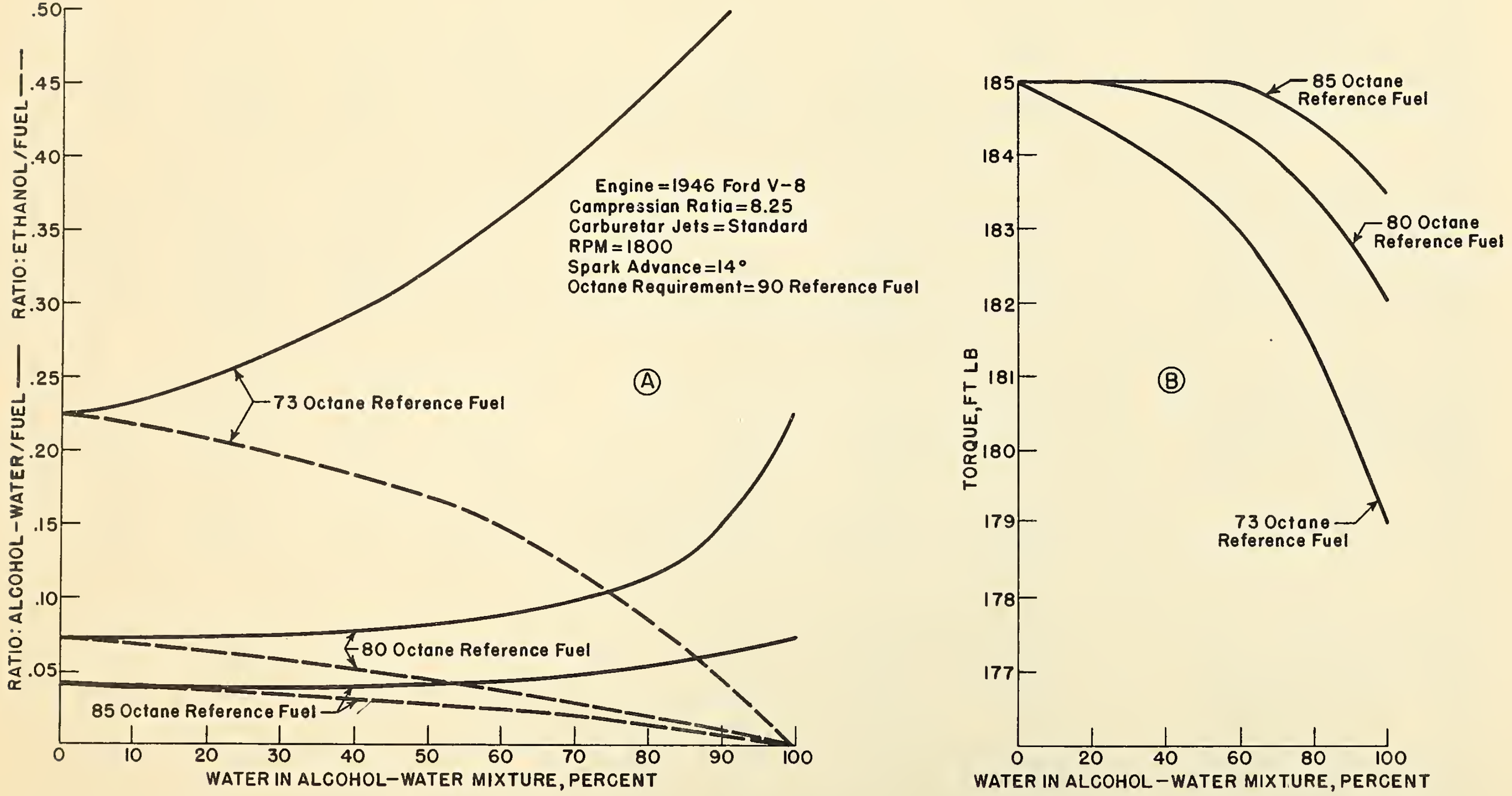

Figure 3.--Effect of the percentage of water in the ethanol-water mixture on the amount of injection required for only trace knock and on engine torque.

TABLE 5.--*Research and Motor octane numbers of four gasolines*

Fuel composition	RESEARCH METHOD A.S.T.M.				MOTOR METHOD A.S.T.M.			
	Plain	+0.5 cc. T.E.L./gal.	+1.0 cc. T.E.L./gal.	+2.0 cc. T.E.L./gal.	Plain	+0.5 cc. T.E.L./gal.	+1.0 cc. T.E.L./gal.	+2.0 cc. T.E.L./gal.
25% Diisobutylene, 75% 50.4 octane Reference Fuel**	76.0	83.6	86.7	90.5	73.8	80.9	84.3	84.5
Blended with 10% ethanol	84.6	88.7	92.7	95.6	79.2	83.6	86.2	87.4
Blended with 25% ethanol	95.2	97.7	98.5	98.8	85.0	86.1	87.0	88.1
Blended with 35% ethanol	100.00	Isooctane + .11 cc.	Isooctane + .14 cc.	Isooctane*** + .14 cc.	87.7	85.9	86.4	87.1
50% Diisobutylene, 50% 15.0 octane Reference Fuel	82.4	87.8	91.6	92.2	74.1	78.0	81.0	82.2
Blended with 10% ethanol	87.6	92.3	94.3	95.2	77.6	80.0	81.8	83.0
Blended with 25% ethanol	95.0	98.0	99.0	99.3	81.8	82.2	82.6	84.1
Blended with 35% ethanol	98.2	Isooctane + .09 cc.	Isooctane + .04 cc.	Isooctane + .10 cc.	84.0	82.7	83.6	83.8
25% Toluene, 75% 63.0 octane Reference Fuel	78.2	84.8	88.3	91.7	73.8	80.6	84.6	87.4
Blended with 10% ethanol	87.1	92.2	94.8	97.2	80.0	84.8	88.1	88.5
Blended with 25% ethanol	97.2	100.0	Isooctane + .085 cc.	Isooctane + .18 cc.	86.4	87.6	87.7	89.8
Blended with 35% ethanol	Isooctane + .08 cc.	Isooctane + .12 cc.	Isooctane + .20 cc.	Isooctane + .29 cc.	87.8	87.2	87.8	89.7
50% Toluene, 50% 45.0 octane Reference Fuel	94.3	89.0	93.0	95.7	74.0	79.7	83.3	85.4
Blended with 10% ethanol	90.1	95.2	97.3	99.2	79.5	83.7	85.6	87.1
Blended with 25% ethanol	97.5	Isooctane + .12 cc.	Isooctane + .24 cc.	Isooctane + .34 cc.	84.6	85.7	86.7	87.1
Blended with 35% ethanol	Isooctane + .11 cc.	Isooctane + .37 cc.	Isooctane + .22 cc.	Isooctane + .28 cc.	88.5	88.2	86.8	90.0

These results were obtained by C. F. Elder and C. R. Martin of this Laboratory.

** Reference fuel is composed of isooctane and n-heptane in the proportion to give the required octane value.

*** Isooctane + .11 cc. means that the octane number of the blend is above 100 octane. On the performance number scale the addition of .11 cc. of lead/gal. is equivalent to 104 where 100 equals the performance of isooctane in a suitable engine.

and toluene with isooctane and *n*-heptane approximate many of the present-day regular gasolines was the reason for their selection. Alcohol-water injection is nothing else but blending of alcohol or alcohol-water with gasoline in the manifold of the engine instead of in the fuel tank.

Table 5 shows, therefore, the resultant octane numbers when alcohol, lead, or a combination of the two is injected in various proportions or used in a straight blend. The Research octane number is most important because it more nearly represents the road rating at low speeds where the octane requirement is highest and the gasoline usually has sufficient anti-knock quality to suppress knock at higher speeds. Duckworth, Moore and Domke *(13)* in an extensive investigation found, for instance, that a 97/85 gasoline will have a road rating of 97 at 20 m.p.h.--a road rating exactly equal to the Research octane number. Such a gasoline would be given by the injection of ethanol to the extent of 25 percent of the gasoline consumption when an unleaded gasoline represented by a 50:50 toluene--isooctane--*n*-heptane mixture is used as the base fuel. According to Scott, Tobias, and Haines *(34)* such a fuel would not quite satisfy the octane requirement of their car "C" with 10:1 compression ratio, missing the goal by two octane units. Their results were obtained with a car in good condition which, unfortunately, is not true in many cases and for an "average" car it would be somewhat higher.

The response of the various compositions to alcohol and lead is of interest in several ways. It is evident that the Research Method number is affected to a much greater extent than the Motor Method number. The addition of 35 percent ethanol to the unleaded 50 percent toluene "gasoline" raises the former by 20 units (isooctane + 0.11 ml. T.E.L./gal. is taken as 104+) while in the latter case the difference is only 14.5, at the same time calling attention again to the fact that the farther up the scale we go, the more effective each octane unit becomes. In general, the same is true for leaded alcohol blends except that the addition of the second cubic centimeter (or milliliter) of tetraethyl lead is frequently not so effective and this raises an important problem in connection with alcohol-water injection. If the gasoline used in connection with alcohol injection is highly leaded, the presence of lead in the injected mixture would be superfluous in such cases. To avoid any misunderstanding, the amounts of lead indicated in table 5 are the amounts present in the gasoline-ethanol mixture in the manifold. For instance, if the amount of ethanol injected happens to equal 35 percent of the volume of gasoline and a total of 1 ml. T.E.L./gal. is required, either the fuel must contain 1.5 cc. of lead per gallon or the injected alcohol a lead concentration equal to roughly 3 ml. T.E.L./gal.

Related to this discussion is the question of octane requirement of present-day cars. One such investigation was made by the Shell Oil Company, and their 1947-1948 survey of passenger car octane requirements *(37)* confirmed the previous statement that the requirement is highest at approximately 20 m.p.h. (1,000 r.p.m. engine speed). It was found that 40, 60, 80, 90, 95, and 99 percent of the cars are satisfied by gasoline having octane numbers of 75, 80, 84, 87, 89, and 93, respectively. The high octane requirements of a considerable proportion of present-day cars is significant with relation to the requirement for higher compression engines.

Some of the test results obtained by driving a 1948 Plymouth sedan and a Ford truck which were available for this purpose are summarized in table 6. The data show

TABLE 6.--*Road test results with automatic injector over same test course of hilly and rolling terrain; both city and country driving; average speed ≐ 33 m.p.h.; in city, 20 to 25 m.p.h., in country, 35 to 45 m.p.h.*

Octane number of gasoline		Average miles per gallon	Average ratio of alcohol-water mixture[1] to gasoline, percent	Carburetor jets	Full-throttle injection rate: ratio: alcohol-water-to-fuel	Percent time[2] injection required	Miles per gallon of anti-knock mixture
Research Method	Motor Method						
			1948 Plymouth sedan				
			Standard head compression ratio 6.6:1				
77	73	19.3	-	standard	-	-	-
58	57	19.4	2.0	standard	0.30	7.0	970
			High-compression head, compression ratio 8:1				
86	86	21.1	-	standard	-	-	-
77	73	21.1	1.5	standard	0.35	4.1	1405
73	73	21.0	1.5	standard	0.34	4.1	1400
			1948 Ford truck chassis weight 5,200 pounds gross weight = 8,500 pounds				
			Standard head-compression ratio 6.75:1				
77.6	73.5	10.1	-	standard	-	-	-
59.0	58.0	10.1	8.5	standard	0.24	18.0	118

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[1] Composition used: 42.5:42.5:15, ethanol-methanol-water.

[2] Injection is required between 7 inches of mercury and wide-open throttle. Injection rate was for trace knock; without injection the particular fuel satisfied the octane requirement of engine.

that the octane requirement of the Plymouth car at normal compression ratio was satisfied by either (*a*) a regular grade gasoline (77/73) or (*b*) a straight-run low-octane 58/57 gasoline with alcohol-water injection, and that in the latter case about 1 gallon of alcohol-water mixture was consumed for every 50 gallons of gasoline. With a high-compression head on the Plymouth the results are more significant. Under these conditions an 86/86 (an insensitive reference fuel was used) gasoline was necessary to prevent more than trace knock and with this, or with regular gasoline plus alcohol-water injection,not only was an increase of almost 10 percent in average miles per gallon obtainable but the amount of injection required for knock suppression was lowered to 1 gallon of anti-knock mixture to every 67 gallons of gasoline.

Furthermore, results of a few preliminary experiments, given in table 6, were obtained in driving a truck with alcohol-water injection over the same test course. As expected, injection was required for a longer time and the amount of injection increased to 1 gallon for every 10 to 11 gallons of gasoline.

The octane requirement and the ratio of alcohol-water to fuel for a maximum 17 octane gain, needed to obtain knock-free operation in two high-compression engines, are plotted versus r.p.m. in figure 4. That the injection curve closely parallels the curve for octane requirement is natural. The reason for the different shapes is not quite so obvious. Ordinarily in the borderline knock procedure, value-in-head engines tend to knock more severely at low speeds than do L-head engines (*31*) without much explanation. The two L-head engines here do not conform to this pattern, but in all this work conformity is the exception and not the rule.

Injection does not take place solely at full throttle or approximately zero vacuum (near atmospheric pressure) but the range will vary with the octane gain desired. This is shown in figure 5-*A*. Not only does the amount of injection decrease with a lower octane gain requirement but injection may be cut off at a lower manifold vacuum (higher absolute pressure). For instance, for maximum octane gain requirements of 21, 15, and 9 (see figure 5-*A*) injection is unnecessary above 9, 7.5, and 6 inches of mercury, respectively, aside, of course, from progressively smaller quantities of alcohol-water mixture to do the job. The peculiar breaks in the curves are caused by the rather "sudden" discontinuance of the power jet operation, a purely mechanical effect. Octane requirement as a function of manifold vacuum is shown in figure 5-*B*.

The effect of increased compression ratio on full-throttle power and economy for a similar engine is clearly demonstrated in figure 6. At 2,000 r.p.m. (approximately 30 m.p.h.) full-throttle specific fuel consumption (S.F.C.) dropped from .58 to .42 and brake horsepower was raised from 65 to 72 when the compression ratio (C.R.) was increased from 6.75:1 to 8.25:1. Taking the power jet out resulted in an increase of air-fuel ratio (A/F) from 12.2 to 15.6.

Returning to actual road experience, the results of R. I. Potter *(29)* are cited in table 7.

Potter's results in general confirm the data in table 6. The considerable gain in economy at higher compression ratios is certainly significant. In this connection it is of interest (*34*) that an improvement of only 1 percent in miles per gallon

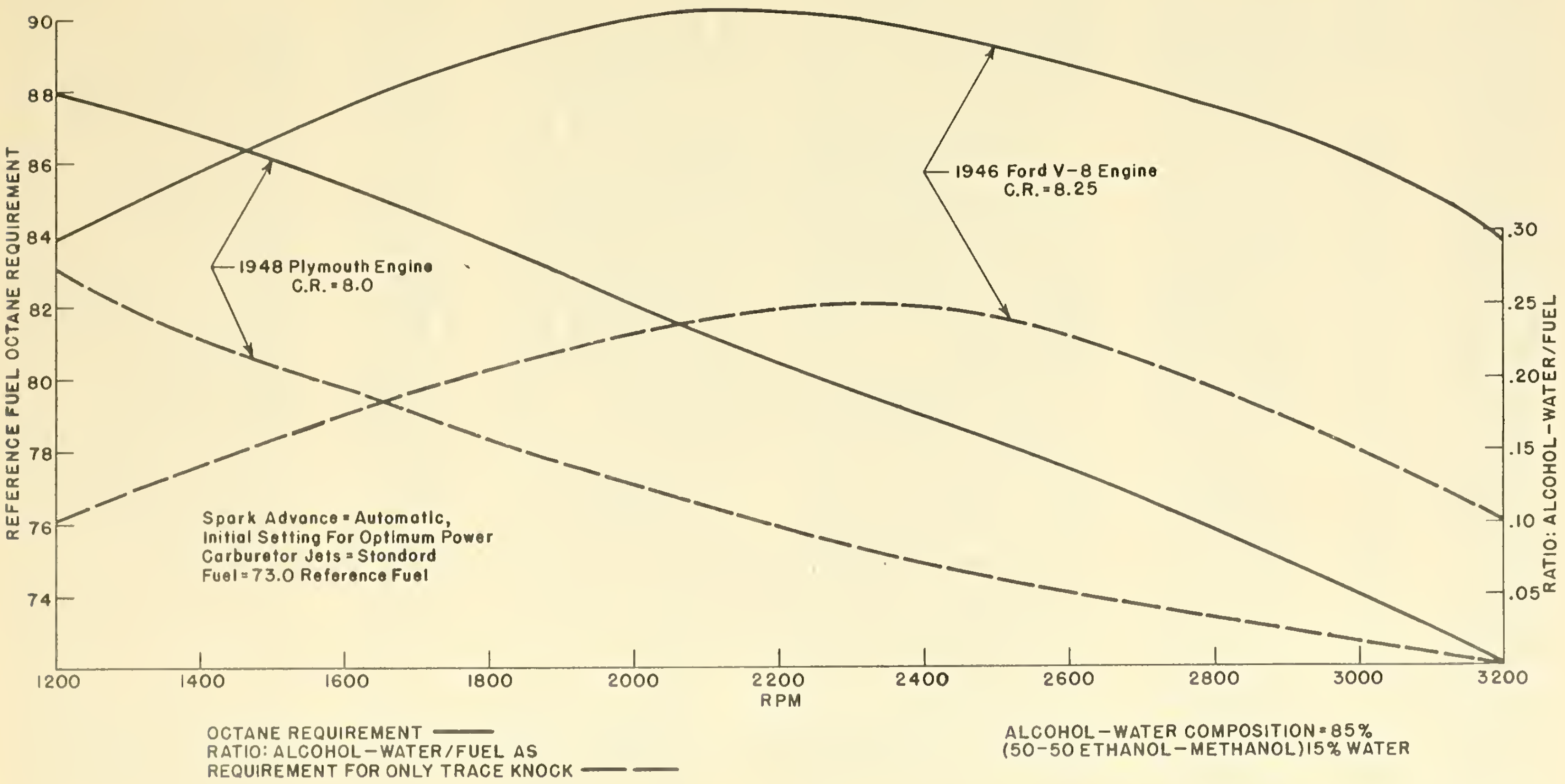


Figure 4.--Injection rate and octane requirement as related to engine speed at full throttle for two L-head, high compression engines.

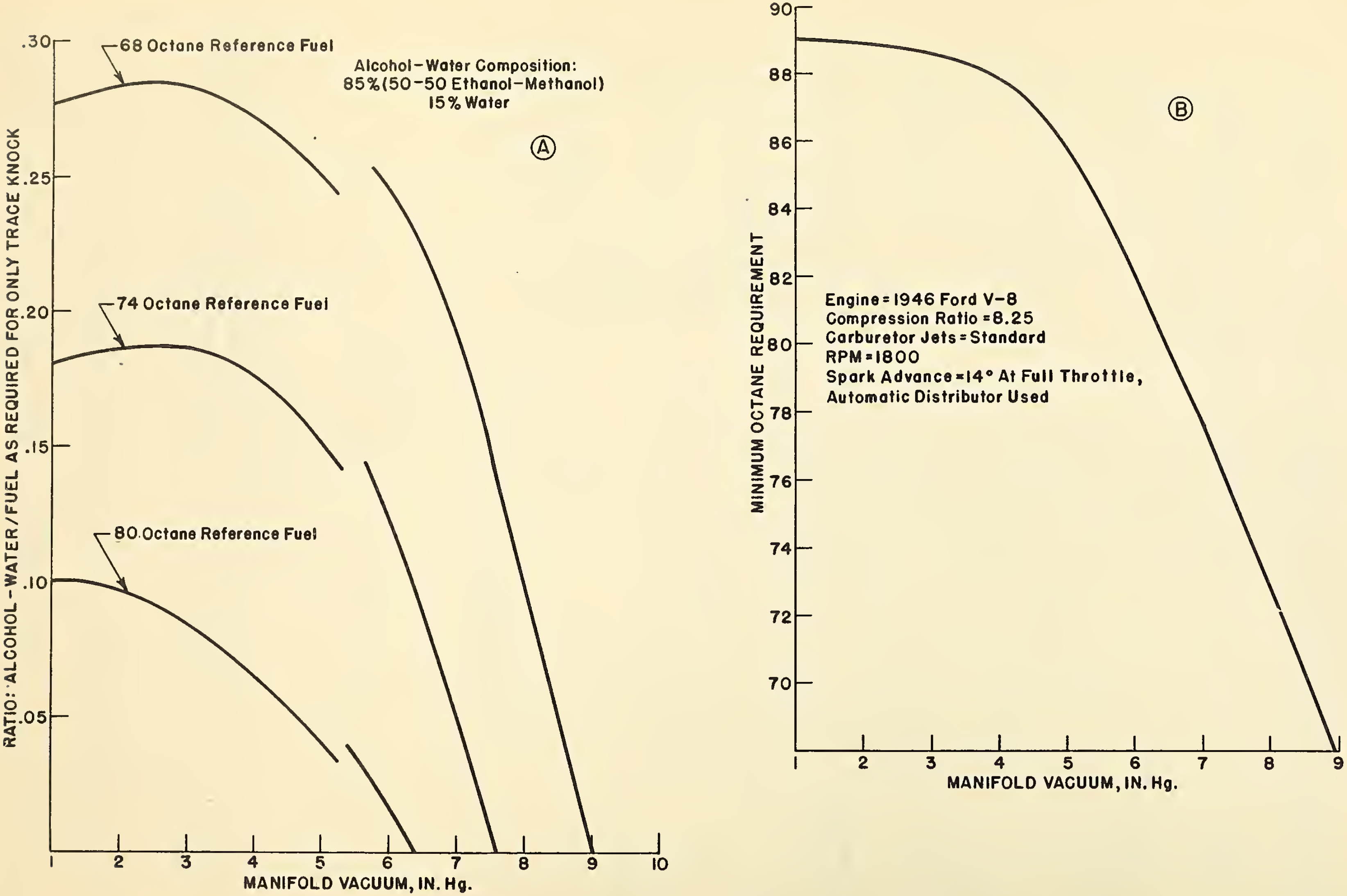


Figure 5.--How manifold vacuum for injection "cut-out" and injection rate required for only trace knock vary with the octane number of the fuel used.

would result in a saving of approximately 7 gallons of gasoline annually per passenger car, since the average car consumes 714 gallons of gasoline in traveling about 10,000 miles per year at 14 miles per gallon. With 31 million passenger cars in use this would mean a reduction in gasoline consumption by 217 million gallons and a saving of more than 50 million dollars at present gasoline prices.

A different approach is given by James *(22)* who assumed the replacement of 1 percent of old cars by an equal number of new cars having a 10-percent lower fuel consumption for the same power output. If this replacement went on for 10 years, an annual saving of 300 million dollars would result.

TABLE 7.--*Results with alcohol-water injection in standard and high-compression automotive engines*

Item	Six-cylinder engine	
	Compression ratio standard	Compression ratio 9:1
Cross-country trips, including some city driving and hilly terrain:		
Miles per gallon of gasoline	19.5	22.2
Percentage increase in miles per gallon		13.7
Percent anti-detonant solution to gasoline used		2.9
Miles per gallon, anti-detonant		771
City trips:		
Mileage per gallon of gasoline	15.9	19.1
Percentage increase in miles per gallon		20.1
Percent anti-detonant solution to gasoline used		8.8
Miles per gallon, anti-detonant		220

What may be expected in present-day cars and trucks is seen in table 8, taken from a paper by Van Hartesveldt, mentioned previously *(36)*.

The practical application in this case presupposes a supply of a relatively low-octane fuel. Again it will be noticed that the amount of alcohol-water injected depends on the type of service.

Figure 7 gives the road octane requirement of the truck engine discussed in connection with table 6 on level road and at loads corresponding to various manifold vacua. On perfectly level road at 40 m.p.h. only a 22-octane fuel is needed to provide knock-free operation. The crossing of the full-throttle curve by the one representing a 3-inch manifold vacuum between 20 and 25 m.p.h. is of interest, and is probably caused by the spark advance mechanism.

TABLE 8.--*Anti-knock mixture consumption*

Type of fleet	Number of vehicles	A.S.T.M. motor octane number of base gasoline	Road octane number increment added	Anti-knock mixture	Gallons of anti-detonant per 100 gallon of gasoline
Tank trucks in bulk and home delivery service	188	63	8-12	45 percent isopropanol-- 55 percent water	5.5
" (1)	188	63	8-12	85 percent methanol,--15 percent water, 3 cc. tetra-ethyl lead	2.0
Tank trucks in bulk delivery service	23	59	19-23	"	5.2
" (2)	23	65	12-14	"	2.8
Tank trucks and trailers	10	59	19-23	"	11.8
" (2)	10	65	12-14	"	6.4
Taxicabs and airport limousines	65} 23}	58	18-25	"	4.0
" (2)		65	12-17	"	2.2

[1] It is estimated that if an 85:15 methanol-water mixture plus 3 ml. of tetraethyl lead is used, a reduction in gallons of anti-detonant per 100 gallons of gasoline from 5.5 to 2.0 is possible.

[2] Using an 85:15 methanol-water, 3cc. tetraethyl lead, in each case, it is estimated that a reduction in gallons of anti-detonant per 100 gallons of gasoline can be accomplished if the base gasoline octane number is increased from 59 to 65.

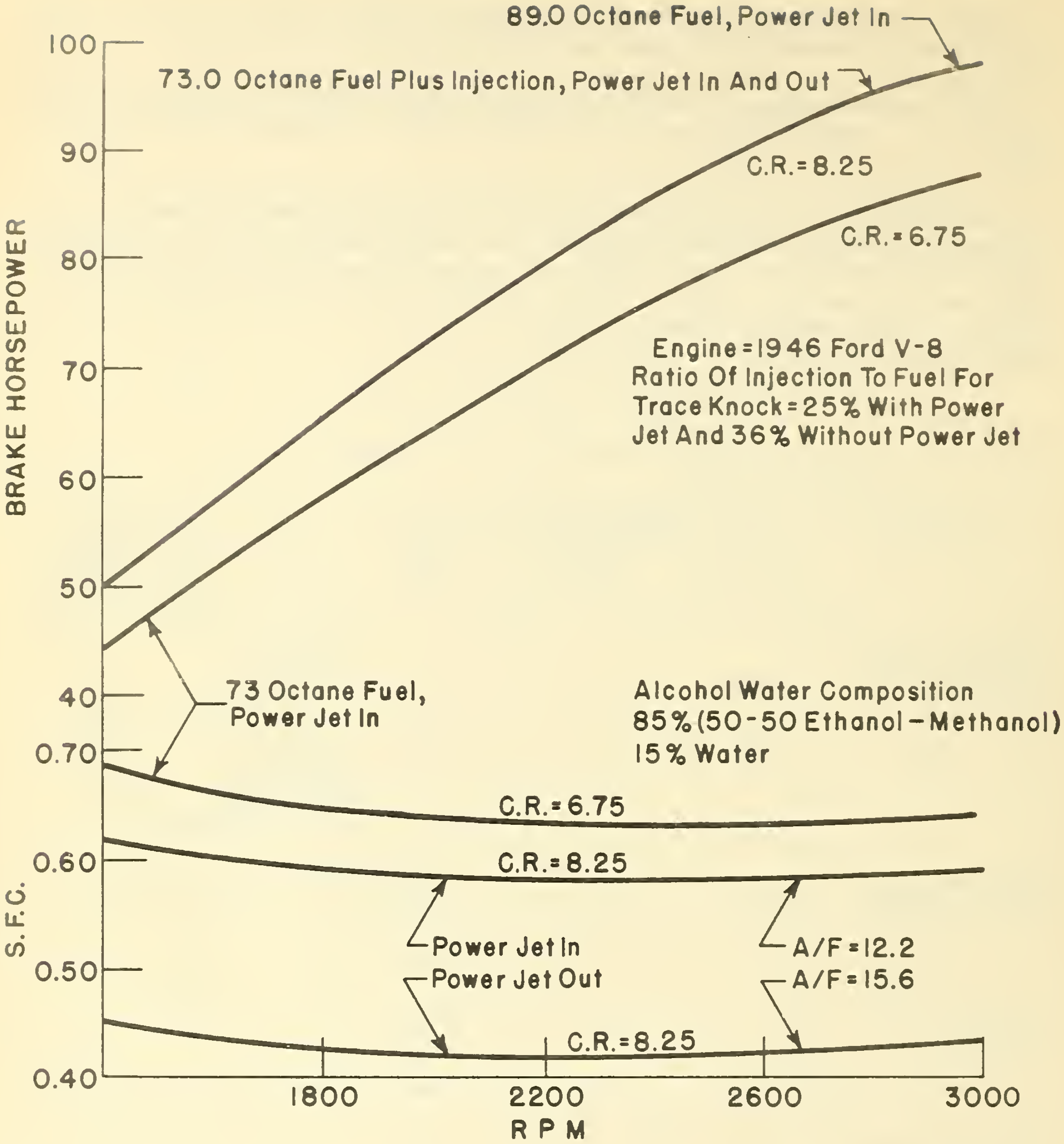


Figure 6.--Full throttle performance curves with alcohol-water injection using an automatic injector.

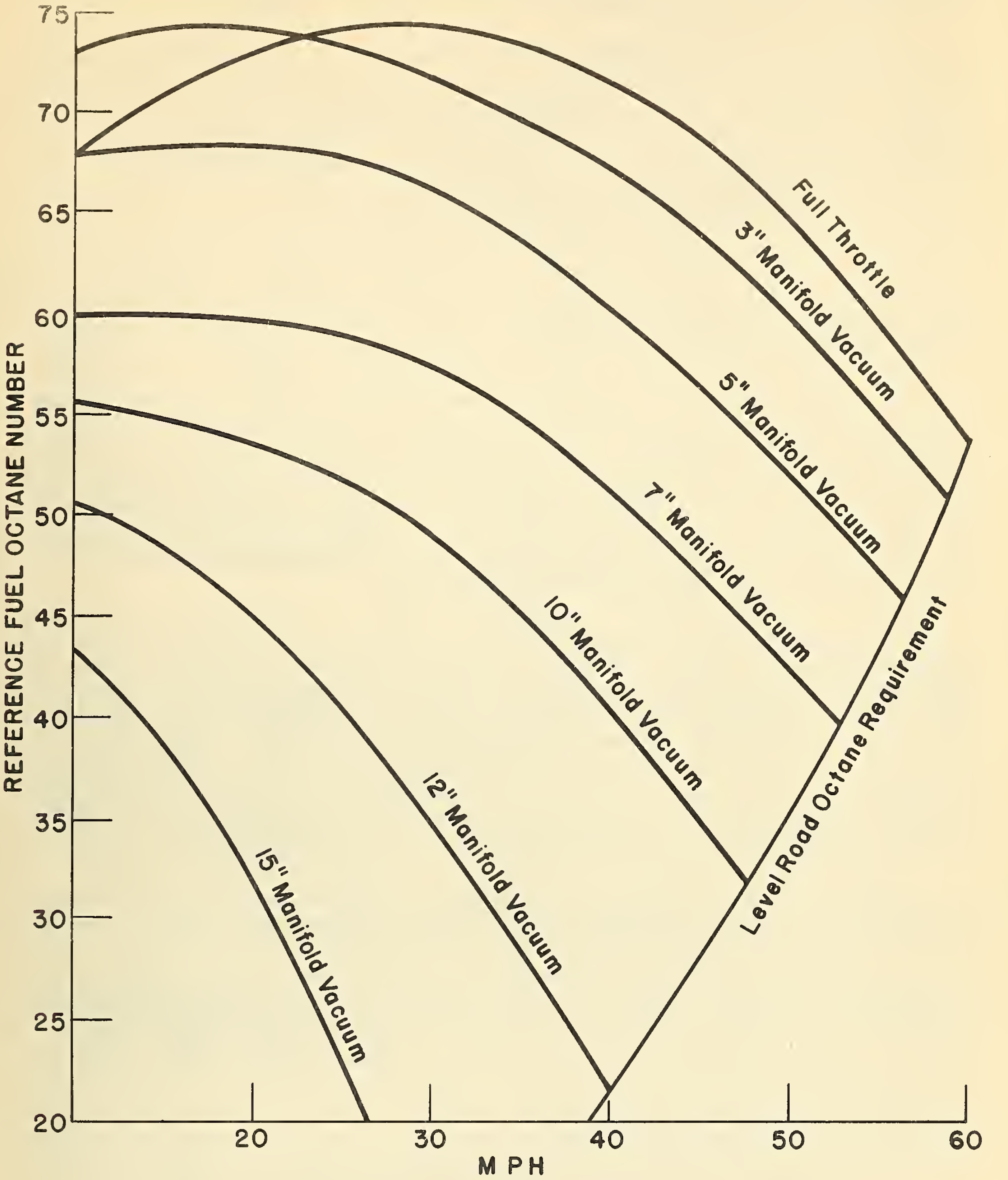


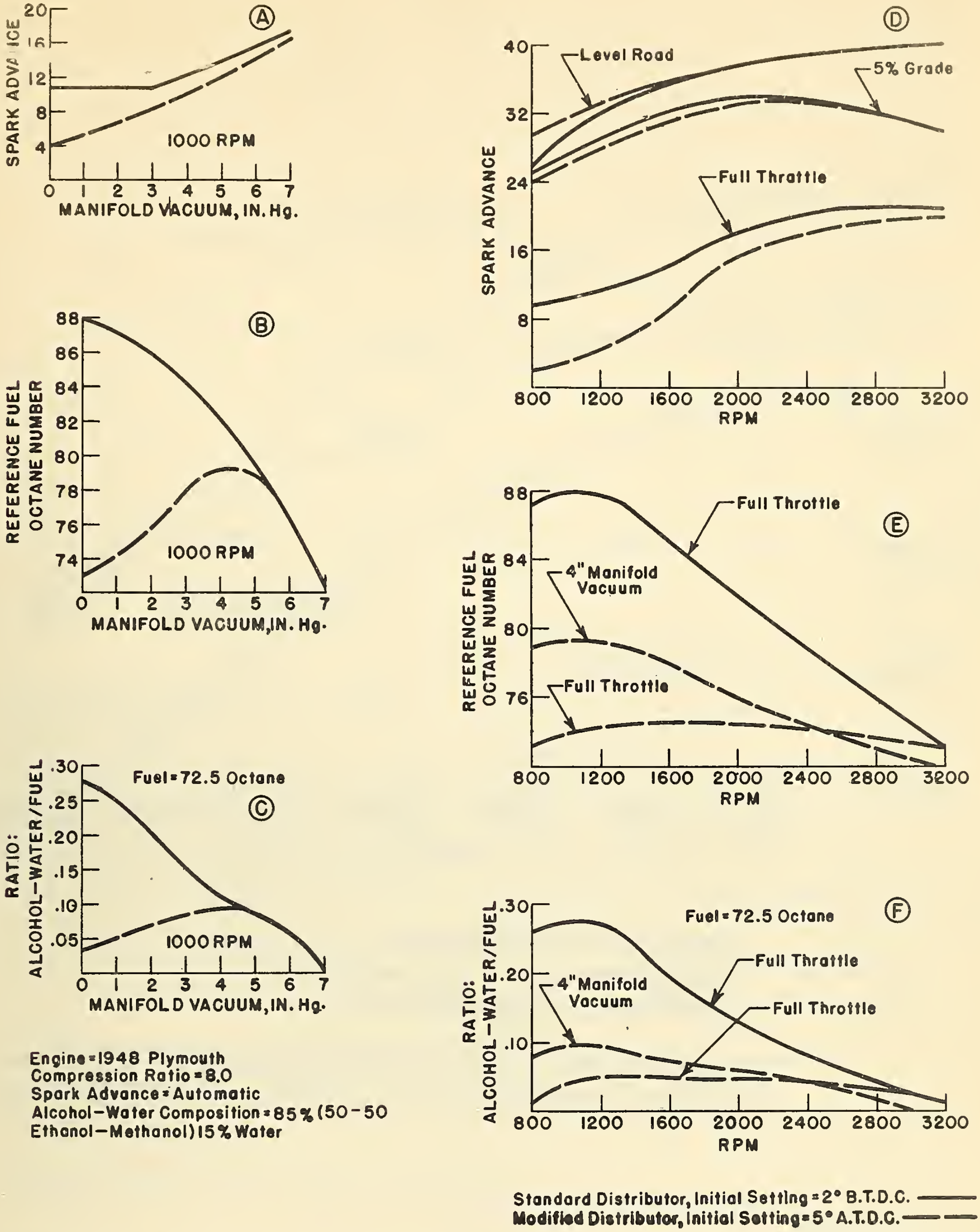
Figure 7.--Octane requirement vs. speed and throttle for a 1948 Ford truck, gross weight--8500 lb. with standard V-8 engine.

Variables present in octane number requirement have been discussed by H. J. Gibson *(16)*. Those of greatest interest here are *(a)* effects of humidity, *(b)* spark advance, and *(c)* deposit accumulation.

A change in humidity from 20 to 90 percent at 70° F. is credited with an average decrease of octane requirement of 4 units. Barber *(3)* states that rather large effects of humidity on octane requirement have been thought to exist at various times but it has not been possible to substantiate them. Variation of absolute humidity from 40 to 129 grains increases the allowable spark advance in the low-speed region. This had previously been observed by Brooks *(8)*, who noted that with the assumption made by him, this would entail an additional loss in power of 13 percent of that caused by humidity. Any effect of moisture is naturally of interest in this discussion since we are dealing with water and alcohol injection. Brooks has dealt adequately with the problem of reduction of output with increased humidity in the form of water vapor in contrast to water in liquid form. The presence of any given volume of water vapor in the cylinder displaces an equal volume of air and proportionately reduces the amount of oxygen available for combustion. This "oxygen content" hypothesis agreed well with experimental results and it appeared that the additional loss in power because of the increase of optimum spark advance was compensated by various conjectured combustion factors such as reduction of heat loss, lower maximum temperatures, specific and dissociation effects. Brooks also mentioned a possible "anomaly." If the carburetor is set very lean, increased humidity will enrich the mixture and give more power on a relative basis, since fuel flow increases slightly with humidity and oxygen content decreases. This anomaly and others may, at least in part, explain some of the increases observed.

According to Gibson *(16)* an increase of 4 degrees in spark advance raises the octane requirement 6 units. A 4-degree variation is probably within the accuracy of most ignition timing mechanisms and a considerable number of cars would have a higher than "normal" requirement even if they were adjusted to manufacturers' specifications. That they are not so adjusted may be gathered from Greenshields and Hebl *(17)*, who found that 25 percent of the 1937 and 1938 cars and 50 percent of 1939 cars were overadvanced; however, fewer 1939 cars were investigated. They concluded that a loss of 2 to 3 percent in power at full load, because of spark retard to prevent knock, is rather insignificant and is taken care of amply by the size of the engine.

The effect of an average 2-percent decrease in maximum power (torque) on octane requirement and alcohol-water injection was investigated at this Laboratory and the results are shown in figures 8, 9, and 10. For this purpose the standard spark advance mechanism was modified in such a way that an initial setting of 5° after top dead center (A.T.D.C.) compared to manufacturer's setting of 2° before top dead center (B.T.D.C.), part-throttle advance was maintained practically intact in a Plymouth engine with a high-compression head. In figure 8 (*A*, *B*, and *C*) spark advance, octane requirement and alcohol-water to fuel ratio are shown successively as a function of manifold vacuum at 1,000 r.p.m. After 3 inches of vacuum, the modified spark advance approaches rapidly the standard curve *A* and this is brought out in *B* and *C* where the modified octane requirement and alcohol-water to fuel ratio curves join the "standard" curves. Both octane requirement and injection are lowered, distinctly indicating considerable saving but it is of interest to note that maximum requirements in both instances are shifted from 0 to approximately 4 inches of vacuum.



Engine = 1948 Plymouth
Compression Ratio = 8.0
Spark Advance = Automatic
Alcohol-Water Composition = 85% (50-50 Ethanol-Methanol) 15% Water

Figure 8.--Effect of engine speed, throttle setting, and effect of spark advance on octane requirement and alcohol-water injection rate requirement.

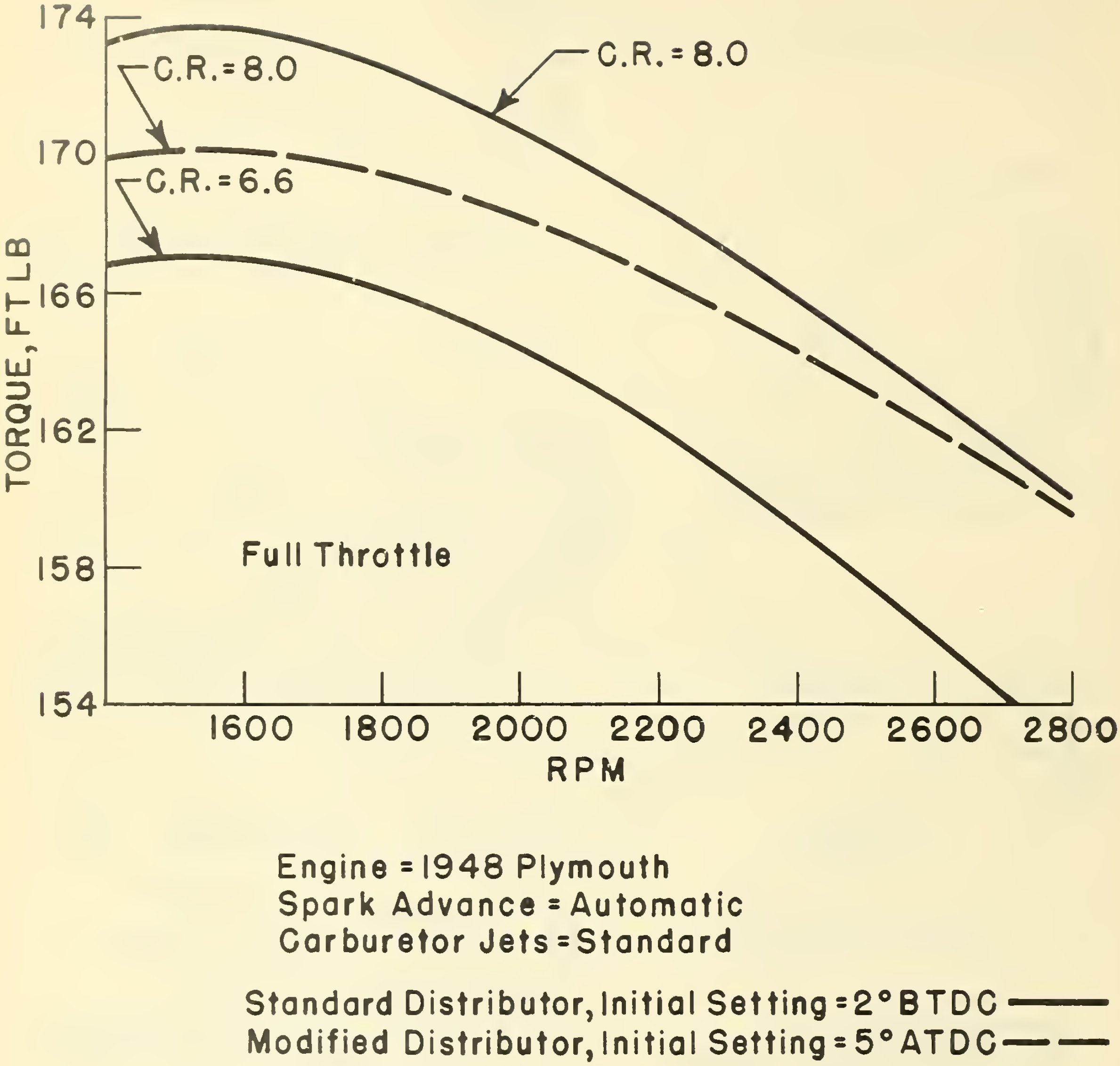
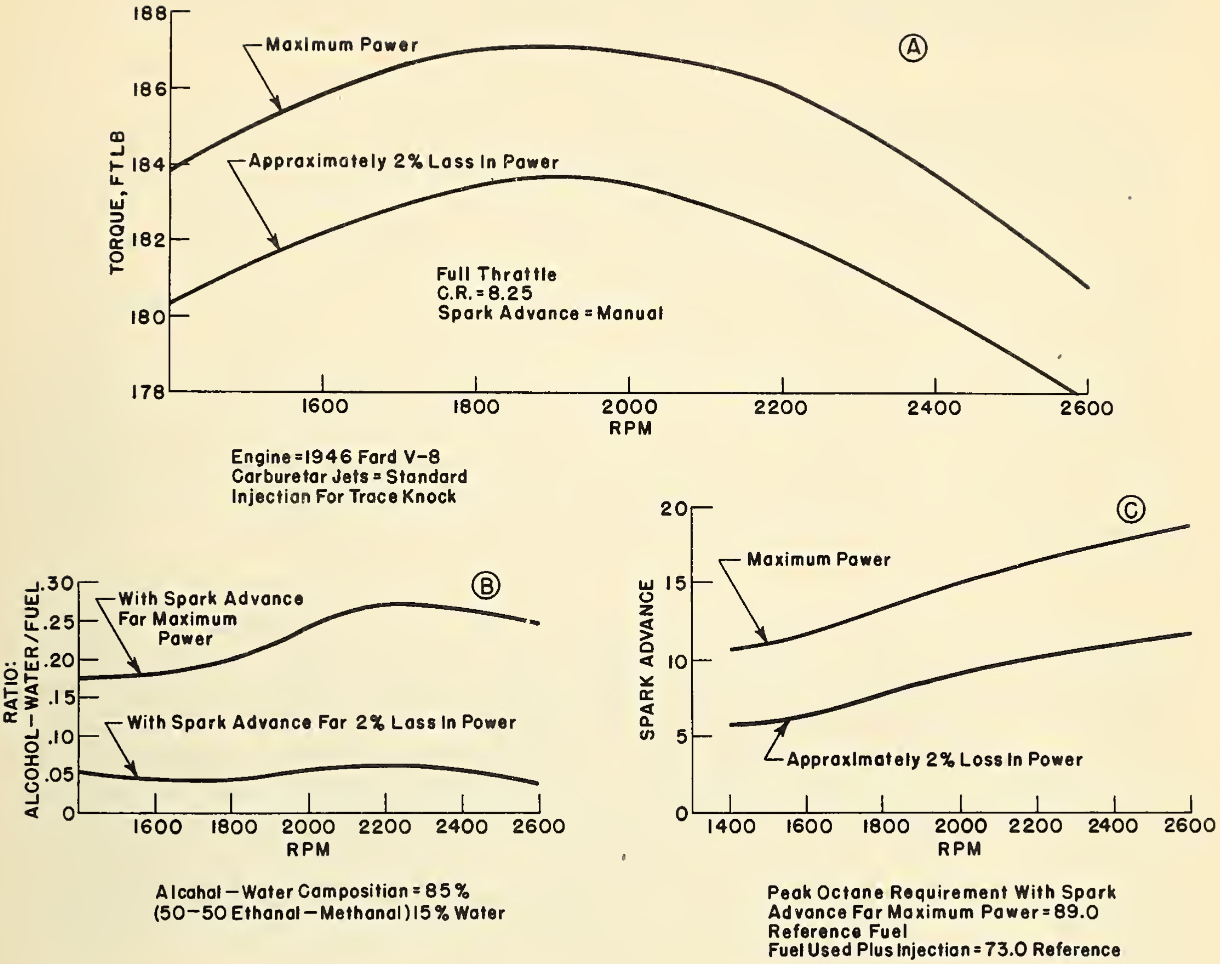


Figure 9.--Effect of modified distributor on full throttle power.



Full Throttle
C.R. = 8.25
Spark Advance = Manual

Engine = 1946 Ford V-8
Carburetor Jets = Standard
Injection For Trace Knock

Alcohol — Water Composition = 85 %
(50—50 Ethanol — Methanol) 15 % Water

Peak Octane Requirement With Spark
Advance For Maximum Power = 89.0
Reference Fuel
Fuel Used Plus Injection = 73.0 Reference

Figure 10.--Effect of spark advance on power and injection rate required.

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Level road and 5-percent grade spark advance were checked and were found to be practically identical with standard setting as shown in *D*. Modified full-throttle advance approached the standard at the higher speeds. In *E* and *F* the changes of octane requirement and alcohol-water to fuel ratio are plotted as a function of engine speed. As noted previously, the 4-inch manifold vacuum octane requirement and, consequently, injection ratio are higher than for modified full throttle, but still considerably lower than standard full throttle which is the highest throughout. Again at high speeds all curves merge. That the higher compression ratio more than compensates for the 2-percent loss is shown in figure 9 where torque is plotted as a function of speed.

With manual spark advance, the effect of a 2-percent loss in power at full throttle was investigated in a Ford engine with a high-compression head. Alcohol-water injection required for trace knock was reduced greatly and should therefore be a very economical means of preventing knock, as shown in figure 10-*B*. In *C* it may be noticed that a 7-degree spark retard was necessary to lower the maximum power by 2 percent. In his very thorough investigation of octane requirement--power--spark advance relationships, Barber *(31)* found that for the engines tested, a 7-degree retard from maximum resulted in 98 percent of maximum power. To prevent any misconception it must be realized that distributors adjusted to manufacturers' specifications of spark timing are not set to give maximum power over the whole speed range. Campbell and Withrow *(9)* show a very interesting plot of spark advance versus octane number with lines of maximum power and 1-, 3-, and 5-percent power loss for one particular distributor. In this case the engine attains maximum power only at high speeds, while at 750 r.p.m. the spark advance is set for an approximately 5-percent power loss.

Although no direct work has been done thus far at this Laboratory on deposit accumulation, engines have remained remarkably clean which in part, at least, must be attributed to the type of operation. That cleaner engines appear to result from alcohol-water injection or, in general, through the use of alcohol fuels, has been stated repeatedly in the literature *(39)*. The problem of deposits is very controversial and aside from the fuel, the effect of lead must be considered. Gibson *(16)* gives an average increase in octane requirement of 9 units for a 10,000-mile deposit accumulation. Barber's results *(3)* are erratic and seem to show that most of the change, if any, occurs during the first 2,000 miles. Type of operation, fuel quality, combustion chamber design, and use of tetraethyl lead are all variables in engine operation. But if alcohol fuels reduce deposits, it would be a positive achievement, though not an answer to explaining the mode of formation of deposits.

CONCLUSION

More efficient engines will require higher octane fuels if present performance standards are to be maintained. The logical step to increase engine efficiency under such conditions appears to be in the direction of higher compression ratios. However supercharging may also come into the picture.

Automotive engines require fuels of higher octane number only at or near full-throttle operation, as for instance during acceleration and hill climbing. Under level road conditions, at uniform speed, the octane requirement is much lower. The principle of alcohol-water injection makes use of this difference in fuel requirement between part-throttle and full-load operation. An alcohol-water mixgure injected under controlled conditions will provide the extra octane needed, thus enabling the engine to operate most of the time on a relatively low-octane gasoline alone.

Aside from alcohol-water injection, dual carburetion may become a possibility for providing high-octane fuels needed for better engines. Holaday (19) described a dual carburetor which would automatically supply either a low- or a high-octane fuel in accordance with the octane requirement of the engine. An improved model is now being manufactured. In this case, high-octane alcohol blends also may be a supplementary source for the needed high-quality fuel.

It is important to remember that here we are dealing not with the distant future, but with the possible present and immediate future need for relative octane improvement. Enough evidence is at hand to show that alcohol-water injection is a distinct possibility as an "octane improver" of gasoline.

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